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Nuclear Energy, Industrial Development, and Economic Growth: Asymmetric Effects on Carbon Emissions in South Asia

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ABSTRACT

The South Asian economies face a two-fold challenge of achieving economic growth and reducing carbon emissions. In this regard, nuclear power has become a potential source of low-carbon energy, but its environmental impact remains controversial. The paper examines the asymmetric effects of nuclear energy, economic growth, and industrial value added on carbon emissions in the nuclear-active South Asian countries using annual data from 1990 to 2024. The panel nonlinear autoregressive distributed lag (NARDL) model is applied to the analysis to capture long-run and short-run asymmetric relationships. Additional diagnostic tests are used to verify that the results are not misleading, including stationarity, causality, and cointegration tests, including panel ARDL estimation, bounds testing, PMG cointegration testing, CUSUM stability tests, and others. The results confirm a long-run stable relationship between the carbon emissions, nuclear energy, economic growth, and industrial value added. The carbon emissions during the positive and negative shocks are seen to increase faster as the economy grows, indicating that the economy is still clinging to fossil-fuel-powered growth. In contrast, the industrial value added reduces the emissions in the long run, which presupposes the role of cleaner production and technological progress. The findings also reveal that nuclear energy has large asymmetric effects: an increase in nuclear energy leads to a decrease in emissions, whereas a shock in nuclear energy leads to an increase in emissions. Overall, the study concludes that nuclear energy can become a potentially efficient source of long-term decarbonization in South Asia if it is accompanied by modernizing the industry and by adherence to policy. The study recommends greater investment in nuclear energy, transitioning industrial processes to low-carbon, and regional energy cooperation to encourage cleaner development in the region.

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1. Introduction

Greenhouse gas (GHG) emissions are widely recognized as a major global environmental challenge, posing serious threats to sustainability and human well-being. Environmental degradation is accelerating in developing economies due to increased industrialization, population growth, and energy consumption, contributing to global warming, rising sea levels, and extreme weather events (Danish et al., 2017). The worldwide community, with the Kyoto Protocol and Paris Agreement, stresses the need to reduce CO2 emissions, the leading cause of anthropogenic climate change (IAEA, 2018). Despite the growing adoption of cleaner energy technologies by developed economies, most emerging economies still rely on fossil fuels because of economic factors and energy security factors (Waheed et al., 2019).

Nuclear energy, in this regard, has become a new topic of academic and policy interest once again as a strategic source of low-carbon energy that can provide a stable baseload power and lessen fossil fuel dependence (Ali et al., 2024b; Islam et al., 2025). Empirical research have shown that nuclear energy is decisive or influential on the reduction of emissions in the long term when institutional capacity, consistency in regulations, and technological readiness are present (Ali et al., 2024a; Wang, Gillani, Nazir, et al., 2024). These new developments illuminate the role of nuclear energy exploration, not only as a source of energy but also as a tool of national policy to promote environmental security in the carbon-rich developing world.

There is recent and organized interest in empirical low-carbon-intensive, that is, there is a multifactor interrelationship between carbon emissions, economic growth, nuclear energy consumption, and industrial performance dimension of graduate empirical studies. A study conducted in different contexts, specifically the United States of America (Baek, 2016), the Organization for Economic Co-operation and Development countries (Lau et al., 2019; Salim et al., 2014), ASEAN economies (Khan et al., 2019), and China (Hassan et al., 2022), indicates, when taken holistically, that an increase in nuclear fuel consumption eventually results in a decrease of CO2 emissions after a time span of relevance analytically. By contrast, many researchers record no impact or adverse environmental consequences associated with nuclear energy and argue that its environmental dividend is not universal across countries, largely due to technological and regulatory disparities (Apergis & Payne, 2012; Jin & Kim, 2018). More recent evidence from Islam et al. (2025) confirms that nuclear energy's environmental effects are asymmetric in nature, meaning increases in nuclear energy may reduce emissions while declines may exacerbate environmental degradation. These nonlinear patterns necessitate the use of asymmetric modeling frameworks to capture real-world dynamics, particularly in developing nuclear economies.

The literature to date has been focused on either country-specific case studies or regional aggregates of a small number of countries. More specifically, no systematic, panel-based analysis of the nuclear energy-environment interface exists, cut across the South Asian region, in particular. However, this sub-continent currently faces rapid economic change, ramping up energy requirements, and national differentiated policy schemes to use nuclear power. Countries like Bangladesh, India, Iran, Nepal, Pakistan, and Sri Lanka represent the highly relevant test cases to assess nuclear power as a decarbonization tool, as the economic progress and environmental sustainability continue to interrelate in these jurisdictions (Sun et al., 2017). However, only India, Pakistan, and Iran currently operate active nuclear power facilities, and previous studies that include non-nuclear countries introduce estimation bias and obscure the true environmental implications of nuclear energy. Therefore, focusing exclusively on these nuclear-producing economies provides more accurate and policy-relevant insights.

Modelling non-linear and asymmetric dynamics in energy environment relationships has also gained analytic value due to contemporary methodological progress. The nonlinear autoregressive distributed lag (NARDL) model that allows the researcher to distinguish between positive and negative shocks included in explanatory variables provides a more complex understanding of the nuclear–CO_2 nexus (Meo et al., 2018; Shin et al., 2014). Such methodological innovations applied to panels of multiple South Asian states have the prospect of producing policy-relevant results and feeding governmental development of consistent energy and environment policies (Wang, Gillani, Razzaq, et al., 2024). Moreover, the linear ARDL model provides additional information regarding the relationship of long-run equilibrium, and a strong comparison between asymmetric and symmetric dynamics can be made. This is a two-model methodology which contributes to the depth of analysis and reliability of empirical results.

This study seeks to explore the possibility of nuclear energy in South Asia as a viable route to stabilizing carbon levels in the nuclear-producing economies of the region by harnessing its variegated impacts on the environmental conditions. In particular, the research should assess the asymmetric long-run and short-run effects of nuclear energy expansion and contraction on carbon emissions because growth in nuclear capacity can promote decarbonization, and a decrease can exacerbate carbon emissions. Moreover, it explores the interaction between economic growth and industrial value added, and nuclear energy in creating environmental changes, and thus provides a detailed structural insight into the emissions curve. This paper aims to understand how nuclear energy acts as a stabilizing factor in the carbon transition and offers empirically based prescriptions on energy governance in fast industrializing nuclear economies through such a study using nonlinear NARDL and verifying the model using linear ARDL.

This study will complement the existing empirical literature on the energy-environment nexus by furnishing policy recommendations that can be implemented by developing economies but wish to balance economic growth and environmental sustainability by introducing new nuclear-producing economies panel evidence. The main strength of this work is that it is the first study that studies active nuclear economies, it uses an asymmetric model to model the actual transitions of energy, and it uses industrial structure as a predictor of emissions. The rest of the paper will be organized as follows: Section 2 consists of a critical literature review of the corresponding literature; Section 3 reports about empirical methodology and data description; Section 4 will report results of the empirical study; Section 5 will discuss policy implications; and Section 6 will conclude the paper with limitations and directions to further research.

2. Literature Review

2.1. Theoretical Perspectives: Energy Use, Economic Growth, and Environmental Quality

Energy consumption, economic development and the quality of environment are the essence of contemporary discussions and research in the academic and political community. Much of this discussion has been pegged into two major theoretical ideas, the Environmental Kuznets Curve (EKC) and the IPAT framework. The EKC hypothesis suggests that there is an inverted U-shaped relationship between environmental degradation and income per capita: economic growth first amplifies pollution, but the growth rate later dies down before an increase in growth leads to better environmental conditions due to innovation in technology and an intensification of administration (Gillani & Sultana, 2020; Lau et al., 2019; Nawaz et al., 2019). Comparatively, IPAT model explains the product of interaction between three factors: population, economic activity, and technological options including energy sources in determining environmental consequences (Danish, Ozcan, et al., 2021).

The use of such theoretical approaches toward the study of energy has shown that energy use that relies on fossils often enhances the release of CO_2 especially in developing countries (Bhatti & Fazal, 2021; Fazal et al., 2020). The adoption of cleaner technologies, the most prominent of which is nuclear energy, on the contrary, has the potential to break this pattern, and lead to decoupling of economic growth and emissions (Ali et al., 2024b; Baek, 2016; Danish, Ud-Din Khan, et al., 2021). The latest work engages these theoretical foundations by adding nonlinear approaches, where the reaction of the environment to energy use may vary with the increasing or decreasing energy consumption with differing levels of the technological progress and policy regimes (Khezri et al., 2024; Mamkhezri & Khezri, 2023). These recent theoretical developments explain why asymmetric models should be used to study the effect of nuclear energy on the environment.

2.2. Nuclear Energy and Environmental Pollution

A comprehensive literature review will indicate that the impact of nuclear energy on carbon emissions remains controversial among various economies. Baek (2016) concluded that nuclear power can be used to dramatically decrease emissions in the United States, supported by Salim et al. (2014) in OECD countries. Lee et al. (2017) also found that nuclear deployment had a negative long-term correlation with emissions. Nevertheless, Apergis and Payne (2012) demonstrated that there is a mixed relationship based on regional aspect, and Jin and Kim (2018) did not establish any significant relationship, indicating that there are differences between countries in terms of technology uptake, energy infrastructure and regulatory framework.

Regional studies indicate that nuclear power can have a radical environmental contribution in certain conditions. Khan et al. (2019) observed its role in lowering emissions in the ASEAN economies. According to Hassan et al. (2020), BRICS countries delivered similar impacts, but the effects were weaker than those of renewable sources. Danish, Ud-Din Khan, et al. (2021) presented evidence that China has strong mitigation potential using nuclear energy at the country level. Recent research stresses generalizing as effects are not homogenous. Mamghaderi et al. (2023) showed that nuclear energy can only minimize emissions when the levels of ecological efficiency are achieved, and Ali, Rahaman, et al. (2025) emphasized the role of geopolitical and institutional factors in the formation of ecological outcomes. These results indicate that the nuclear-environment nexus is heterogeneous and atmosphere-dependent and demands highly developed econometric treatment.

2.3. Nonlinear and Asymmetric Relationships: Advancements in Methodology

Conventional linear models can simplify the nexus between energy and environment, by effectively and symmetrically responding to energy shocks. The nonlinear autoregressive distributed lag (NARDL) model breaks down energy variables into positive and negative variables and provides an asymmetric effect (Shin et al., 2014). The researchers by Meo et al. (2018) have shown that the effect of positive and negative energy shocks varies on the emissions. Mahmood et al. (2020) have found that nuclear energy is nonlinear in Pakistan. New methodological developments also continue to favor this asymmetrical treatment. The NARDL was used by Khaliq and Mamkhezri (2023) to analyze the environmental complexity in South Asia and confirm asymmetric reactions to the environment, whereas Khaliq et al. (2023) demonstrated that asymmetric shocks in energy trade have a considerable effect on emissions. These modern works support the application of nonlinear schemes in the modelling of the environmental effect of nuclear energy.

2.4. Industrial Productivity, Economic Growth, and CO_2 Emissions

Environmental outcomes mainly depend on industrial value added (IVA) and economic growth. Although the growth of the economy is commonly associated with an increase in emissions among fossil-fuel-reliant economies (Danish & Wang, 2019; Waheed et al., 2019), it can be reduced with the help of industrial modernization, regulations, and clean technologies (Xie et al., 2025). Chen and Santos-Paulino (2013) indicated that transformation in the industry has the potential to lower emissions. Tiwari (2011) pointed out the same trends in India. However, current studies reveal that technological innovation and industrial productivity based on R&D are critical in environmental efficiency (Mamkhezri & Khezri, 2023). Ali et al. (2024b) discovered that economic growth has an unequal impact on the environment in relation to institutional and structural conditions. Islam et al. (2022) added that the energy-environment nexus in the ASEAN economies implies the mediating role of institutional quality, which strengthens the importance of industrial value added as a primary variable in the environmental model.

2.5. Regional Evidence from South Asia and the Need for Panel Analysis

In South Asia, there has been scanty empirical research on the environmental impacts of nuclear energy, although the world is interested in this. Danish, Ozcan, et al. (2021) revealed that the country of India has potential emissions cut, but energy structure is a crucial factor. Syed (2021) suggested a regional strategy due to the swift energy shifts and contradictory national policies. The panel data design enables thorough investigation across nation borders managing unobserved heterogeneity and both short and long-term dynamics (Pesaran et al., 2001). Recent literature reveals that the effects of nuclear energy are skewed and unbalanced in South Asia, and a combination of nuclear and non-nuclear countries will come up with unfair findings (Khaliq & Mamkhezri, 2023). Hence, concentrating on India, Pakistan and Iran alone gives a real picture of the environmental implications of nuclear energy.

2.6. Research Gap

The critical analysis of the available literature indicates conceptual, methodological, and contextual constraints. Most studies have used linear models and do not consider the asymmetric dynamics in the consumption of nuclear energy. Nuclear and non-nuclear economies are aggregated by others where the distinct environmental effects of nuclear power are diminished. Moreover, the countries producing nuclear power in South Asia have received little priority in research efforts despite increasing their energy requirements and the strategic energy decarbonization function in the world. This paper addresses these gaps by using a nonlinear panel NARDL model to examine asymmetric impacts of nuclear energy, economic growth, and industrial value added on carbon emissions in India, Pakistan, and Iran. The current research is more specific and policy directed as it provides a more accurate and up-to-date perspective on the impact of nuclear energy on the environmental quality in a dynamic setting.

3. Data and Methodology

This paper uses the annual panel data of three South Asian economies India, Iran and, Pakistan between 1990 and 2024. The countries are selected because of the presence of consistent data on nuclear energy consumption, industrial output and environmental indicators. The variables that will be used in this analysis are carbon dioxide emissions per capita (CO2), economic growth (GDPG), industrial value added (IVA), and nuclear energy consumption (NE). Carbon dioxide emissions are expressed in metric or kilograms and are derived at the World Bank under world development indicators (WDI). Economic growth is measured by the annual percentage growth rate and industrial value added is an added value of industry including construction to GDP. The share of alternative and nuclear power in the national energy mix is determined as a percentage of alternative and nuclear energy and is known as nuclear energy (see Table 1).

This study is based on the empirical model that is based on both the Environmental Kuznets Curve (EKC) and the IPAT frameworks, where energy consumption is strongly affected by economic activity and environmental conditions, which works in a dynamic manner and possibly in a non-linear manner. In line with the recent research (Baek, 2016; Khan et al., 2019; Syed et al., 2021), the general form of the panel analysis can be provided as:

$$CO2_{it} = f(GDPG_{it}, IVA_{it}, NE_{it}) \quad (1)$$

The novelty of the presented investigation is that it uses the Panel Nonlinear Autoregressive Distributed Lag (Panel NARDL) model which can simultaneously model short-run and long-run, and asymmetric, relationships between explanatory variables and CO_2 emissions. Traditional linear specifications are not always able to capture such nuances whether an increase or a decrease in volumes of nuclear energy, economic growth, or industrial value-added produce different effects on environmental pollution. In contrast, the

NARDL model introduced by Shin et al. (2014) splits each predictor into positive and negative summands, thus, making it easier to identify asymmetric effects in an empirical manner. The approach is especially useful when considering energy and environmental issues in developing nations where policy changes and technological transitions are likely to result in nonlinear emissions trends (Syed, 2021; Yang, Shafiq, Sharif, et al., 2024).

Table 1
Variables Description

Variable	Abbreviation	Measurement	Source
Carbon Emissions	CO2	Carbon dioxide (CO2) emissions excluding LULUCF per capita (t CO2e/capita)	WDI
Economic Growth	GDPG	GDP (annual % growth)	WDI
Industry Value Added	IVA	Industry, including construction, value added (annual % growth)	WDI
Nuclear Energy	NE	Alternative and nuclear energy (% of total energy use)	WDI

The Panel NARDL model can be formally expressed as follows:

$$\Delta CO_{2it} = \alpha_i + \lambda_i\left[CO_{2it-1} - \beta_1 GDPG^{+}_{it-1} - \beta_1 GDPG^{-}_{it-1} - \beta_2 IVA^{+}_{it-1} - \beta_2 IVA^{-}_{it-1} - \beta_3 NE^{+}_{it-1} - \beta_3 NE^{-}_{it-1}\right] + \sum_{p=1}^{P}\gamma_{1p}\Delta CO_{2it-p} + \sum_{q=0}^{Q}(\theta^{+}_{1q}GDPG^{+}_{it-1} + \theta^{+}_{2q}IVA^{+}_{it-1} + \theta^{-}_{2q}IVA^{-}_{it-1} + \theta^{+}_{3q}NE^{+}_{it-1} + \theta^{-}_{3q}NE^{-}_{it-1}) + \epsilon_{it} \quad (2)$$

In this formulation, Δ denotes the first-difference operator; α_i represents country-specific fixed effects; λ_i is the error correction term; β^{+} *and* β^{-} are the long-run coefficients for positive and negative changes in the regressors; γ and θ are short-run dynamic coefficients; and ϵ_{it} is the disturbance term. Each regressor economic growth, industrial value added, and nuclear energy consumption is decomposed into its respective positive and negative partial sums, denoted by the following equations:

$$X^{+}_{it} = \sum_{j=1}^{t}\max(\Delta X_{ij,0}) \quad (3)$$
$$X^{-}_{it} = \sum_{j=1}^{t}\max(\Delta X_{ij,0}) \quad (4)$$

where X stands for each independent variable (GDPG, IVA, NE).

The use of partial sum decomposition captures the asymmetric impact of expansions versus contractions in nuclear energy, which is theoretically and empirically supported in the energy-environment literature. The inclusion of a squared nuclear term (NE^2) is not necessary because asymmetry is already modeled through this decomposition, and introducing NE^2 may create multicollinearity without adding explanatory power.

The estimation strategy follows several steps to guarantee the soundness of the results in addition to the soundness. The study first uses panel unit root tests, namely the Levin, Lin and Chu (LLC) as well as the Im, Pesaran and Shin (IPS) tests to determine the stationarity characteristics of each of the variables (Pesaran et al., 2001). These tests ensure that none of the variables are integrated in order two, a requirement for valid NARDL estimation. Next, the direction of causality among the variables is examined using the Dumitrescu-Hurlin panel Granger causality test, which accommodates cross-sectional heterogeneity and is suitable for relatively short panel dimensions (Dumitrescu & Hurlin, 2012).

The estimation process was carried out following the identification of integration characteristics of the Panel NARDL model and establishment of causality direction to explain, in the short-run and in the long-run, the asymmetric impacts of economic growth, industrial value added, and nuclear energy on carbon emissions. The optimal lag lengths were selected using the Schwarz Information Criterion (SIC) and thus, it was an attempt to find a balance between parsimony and explanatory power. A bounds-testing procedure was used to determine the cointegration relationship in the long-run between the variables (Pesaran et al., 2001). Wald tests were conducted on coefficients of positive and negative changes in each of the explanatory variables to determine whether there is asymmetry in both the short and the long run.

The Panel ARDL model is employed as the baseline due to its ability to estimate both long-run and short-run relationships concurrently while accommodating mixed integration orders and endogenous regressors. To identify asymmetric shocks, the study uses the Panel NARDL framework, which splits the explanatory variables into positive and negative changes as partial sums, which allows the detection of asymmetric effects (Shin et al., 2014). This stands out as compared to linear models that have symmetry in adjustment mechanisms. The NARDL model can represent the intricate real-life adjustment patterns by including such decompositions of the equations 3 and 4 to provide insights that are relevant to policymaking in energy economics.

4. Results and Discussion

To examine the complex relations between carbon emissions, economic growth, industrial value added and nuclear energy consumption in South Asian countries, this section reports and discusses the empirical results of a panel NARDL analysis, supporting tests, and diagnostic tests. The present research, integrated with the theoretical literature in the field of environmental economics, advances to the empirical evaluation step by step of the obtained results. The summary statistics of the key variables are provided in the initial step, and the properties of the unit-root of the key variables are discussed. The subsequent stages examine tests of causality, short and long-run dynamic specifications, cointegration evidence and nation-specific variation. Each stage is framed in relation to the theoretical basis on which it is premised and is compared with the work that has been done before, hence giving a coherent illustration of the overall impact of the integrated forces of economic and energy to the environmental performance in the region. It is also concerned about the policy implications and the soundness of the results to make both evidence-based and sustainable development strategies-consistent conclusions.

Table 2 shows the descriptive data of CO2 emissions, economic growth, industrial value added and nuclear energy consumption in India, Iran and Pakistan, making it apparent that there is a great diversity that indicates the heterogeneous economic structures, level of industrial development and the strategy of energy transition among the three nuclear economies. The CO2 and nuclear energy consumption mean are relatively high, and they signify the active use of nuclear energy as a component of the energy mix, whereas the difference between maximum and minimum values is quite wide and indicates that the environmental results have varied over time because of the changes in policy, technological advancement, and geopolitical forces. GDPG and IVA have high standard deviations that are indicative of economic volatility that is consistent with both periods of high and fast industrial growth, and recessionary shocks.

Table 2
Summary Statistics

Statistic	CO2	GDPG	IVA	NE
Mean	2.844	4.519	4.476	2.913
Median	1.187	4.719	4.874	2.850
Maximum	8.694	13.594	18.786	12.890
Minimum	0.564	-5.777	-13.412	0.220
Std. Dev.	2.757	3.288	5.292	2.101
Skewness	0.961	-0.381	-0.348	1.732
Kurtosis	2.267	3.738	4.599	8.680
Jarque-Bera	18.532	4.937	13.322	193.736
Probability	0.000	0.084	0.001	0.000
Sum	298.721	474.564	470.019	305.890
Sum Sq. Dev.	790.775	1124.349	2913.104	459.138
Observations	105	105	105	105

In addition, non-normality of the series, as detected by large Jarque-Bera values and asymmetric skew and kurtosis value, means that there are structural discontinuities and non-linear reactions in the environmental indicators. These distributional properties give good empirical reasons as to why the Panel NARDL approach should be used where asymmetries in relationship and heterogeneous adjustment dynamics are specifically aimed at to give a better reflection of how rises and falls in nuclear energy consumption, business activity, and economic growth are different in affecting carbon emissions in the long and short-term.

Table 3 shows the correlation coefficients between CO2 emissions, economic growth, industrial value added, and nuclear energy consumption, which important information about the actual relationships in nuclear driven South Asian economies can be drawn. There is a negative relationship between CO2 emissions and GDPG, IVA and NE, with the strongest negative relationship between nuclear energy and the emissions (r = -0.648), supporting that increasing nuclear energy use can be visibly linked with the necessity to reduce the emissions, which supports the evidence presented above of the strengths of nuclear-driven strategies of energy transition. The relationship between GDPG and IVA (r = 0.827) is a positive and strong relationship, indicating that the growth of industry is directly related to the growth of the economy, characteristic of developing economies during the early industrialization period. The values of all correlations do not exceed the critical value of 0.90, which indicates that multicollinearity does not exist and, therefore, the use of this data in the regression model is valid, and there is no risk of distorted coefficients estimates. These correlational trends reinforce the theoretical assumption that nuclear energy is a decarbonizing effect, but industrial activities and economic growth can be viewed as the possible source of environmental pressure, hence the utility of an asymmetric model like Panel NARDL to conceptualise these subtle motions further.

Table 3
Correlation Matrix

	CO2	GDPG	IVA	NE
CO2	1	-0.250	-0.241	-0.648
GDPG	-0.250	1	0.827	0.033
IVA	-0.241	0.827	1	0.0007
NE	-0.648	0.033	0.0007	1

Table 4 shows the outcome of the multicollinearity cheque on Variance Inflation Factor (VIF). The VIF values for GDP growth (GDPG) and industrial value added (IVA) are 3.18, while nuclear energy (NE) has a VIF of 1. All values are well below the accepted benchmark threshold of 10, indicating the absence of harmful multicollinearity among the explanatory variables. Additionally, the tolerance values (1/VIF) are all greater than 0.10, further confirming that no variable poses a risk of inflating the standard errors due to high correlation with other predictors. These results validate the econometric robustness of the model and confirm that each independent variable provides unique explanatory power in determining variations in carbon emissions. Therefore, the model’s estimates may be interpreted with confidence, as the reliability of coefficient significance is not compromised by multicollinearity issues.

Table 4
VIF Test

Variable	VIF	1/VIF
GDPG	3.18	0.314043
IVA	3.18	0.314403
NE	1	0.996494

Table 5 reports the results of the Levin, Lin & Chu (LLC) and Im, Pesaran and Shin (IPS) panel unit root tests, which demonstrate that carbon emissions (CO_2), nuclear energy consumption (NE), economic growth (GDPG), and industrial value added (IVA) are non-stationary at level but become stationary after first differencing, confirming their integration of order one, I(1). The null hypothesis of a unit root is rejected at level and later at the level of first difference, which is the rejection of the null hypothesis at level one and its rejection later on the level of first difference implies that these variables are subjected to the same stochastic processes and must be estimated using a cointegration-based estimation framework to prevent the spurious regression. These findings support the application of the Panel NARDL approach, which is purposely developed to support both mixed-order (integrated I(0)-I(1)) variables and significant equilibrium between long-run and short-run dynamics. All the variables also confirm I(1) properties thus confirming the use of the bounds testing method of testing cointegration and that the nonlinear asymmetric effects are handled in the research are both empirically and econometrically valid.

Table 5
Unit Root Tests

Variable	Levin, Lin & Chu (LLC)				Im, Pesaran and Shin (IPS)			
	At Level		At 1st Difference		At Level		At 1st Difference	
CO2	1.282	0.900	-3.634	0.000	0.447	0.672	-3.305	0.000
GDPG	-6.263	0.000			-4.999	0.000		
IVA	-4.480	0.000			-4.874	0.000		
NE	0.678	0.7513	-2.257	0.012	0.636	0.737	-4.423	0.000

Table 6 shows the findings of Granger causality and Dumitrescu-Hurlin panel causality tests that indicated significant dynamic interdependencies of carbon emissions, economic growth, industrial activity and nuclear energy consumption in nuclear-driven South Asian economies. The two-way causality of the CO2 and GDP growth is a confirmation of the feedback hypothesis, that economic growth heightens emissions and the increasing environmental strains could also drive the growth patterns in a regulatory and technological manner, which align with the EKC model. Additionally, the causality between CO2 and industrial value added implies that the process of environmental degradation can directly translate into industrial productivity, which might be facilitated by the emissions regulations or the energy supply alteration. Notably, the one-way relationship between CO2 and nuclear power is that increasing emissions causes the use of nuclear energy as a response mechanism towards environmental degradation helping to prove the thesis that nuclear power is a policy-oriented energy source though not an unadulterated economic result. Weak causality of economic or industrial activity to nuclear energy also underscores the policy conditionality of relativity regarding nuclear growth in these nations. These causal dependencies reinforce the need to adopt a dynamic disequilibrium model like the Panel NARDL model since it can enable the consideration of feedback effects and nonlinear realignment unlike traditional static causality frameworks.

Table 6
Granger Causality Test

Null Hypothesis	Granger Causality			Dumitrescu Hurlin		
	Obs.	F-Stat.	Prob.	W-Stat.	$\bar{Z}$-Stat.	Prob.
GDPG does not homogeneously cause CO2	99	0.003	0.996	0.428	-1.284	0.198
CO2 does not homogeneously cause GDPG		4.634	0.012	2.894	0.551	0.581
IVA does not homogeneously cause CO2	99	0.689	0.504	1.757	-0.294	0.768
CO2 does not homogeneously cause IVA		5.247	0.006	7.554	4.020	5.805
NE does not homogeneously cause CO2	99	2.992	0.054	2.006	-0.109	0.912
CO2 does not homogeneously cause NE		4.691	0.011	4.749	1.932	0.053
IVA does not homogeneously cause GDPG	99	1.260	0.288	3.541	1.033	0.301
GDPG does not homogeneously cause IVA		1.497	0.229	2.437	0.211	0.832
NE does not homogeneously cause GDPG	99	3.234	0.043	3.114	0.715	0.474
GDPG does not homogeneously cause NE		1.114	0.332	3.486	0.992	0.321
NE does not homogeneously cause IVA	99	1.261	0.288	1.586	-0.422	0.672
IVA does not homogeneously cause NE		0.794	0.454	3.199	0.778	0.436

In table 7, the long-run asymmetric growth coefficients show that positive and negative shocks to GDPG attract carbon emissions in large proportions, which shows that changes in economic activity, expansionary and contractionary, serve to aggravate pressure on the environment in the nuclear economies discussed. The result confirms the first stage of the Environmental Kuznets Curve, according to which, as the countries are developing, their industries develop, and the CO2 emissions increase due to the increased use of energy resources (Ali, Islam, et al., 2025; Lau et al., 2019). Interestingly, even negative GDP shocks also lead to the increase of emissions, which suggests that the sources of emissions are structurally rigid, e.g. the heavy dependence on fossil fuels, despite the existence of adverse economic effects in the short run. This aligns with the recent evidence provided by Khezri et al. (2024), who concluded in a study on the reduction in emissions that in economies with low levels of renewable penetration, decreases are not necessarily prone to occur when the economy slows down, and energy-intensive industries continue to operate due to the necessity of the given baseline consumption levels. In general, the findings indicate that the economic growth of nuclear economies is still carbon-related, which again supports the necessity of switching to low-carbon technologies to overcome the growth-pollution nexus.

The negative and significant coefficients at long-run of both the positive and negative shocks on industrial value added indicate that increases/decreases in production by industry are linked with decreases in carbon emissions implying that there are technological upgrading and cleaner industrial processes in these countries. This finding is consistent with the IPAT framework, which assumes that there is no need to reduce the environmental degradation caused by industrial expansion through technological innovation (Danish, Ozcan, et al., 2021). The recent empirical study by Mamghaderi et al. (2023) also emphasises that the increase in industrial efficiency and environmental control in the developing economies leads to the decrease in the intensity of emissions. Moreover, the negative correlation demonstrates a possible decoupling effect, in which industrial productivity-driven economic activities cease to lead to corresponding increases in emissions because of the use of less carbon-intensive-based technologies and structural changes to less carbon-intensive industries (Chen & Santos-Paulino, 2013; Destek, 2016). This proves that industrialization can bring positive results to the environment when supplemented with clean technology and policy actions to improve it instead of eroding it.

The asymmetric coefficients of nuclear energy consumption reveal that positive shocks considerably decrease carbon emissions, evidencing that learning to use nuclear energy as a low-carbon alternative is the element able to substitute the use of fossil fuels in the production of the power. This result is consistent with the long-standing hypothesis of energy transition and current empirical findings Khaliq and Mamkhezri (2024); Mamghaderi et al. (2023) that also focus on the efficiency of nuclear energy in decarbonizing growing economies. The positive value however in negative shocks (NE_NEG) indicates that a decrease in consumption of nuclear energy will have an increase in emissions, indicating a fallback to use of carbon-intensive energy sources when nuclear supply is interrupted. Simultaneously, Jin and Kim (2018) outline similar findings, noting that intermittent nuclear production triggers the reliance on coal and oil, annulling the environmental advantages of nuclear use. The findings reinforce the strategic value of nuclear capacity stability in the wake of requiring decarbonization processes and maintaining environmental security in the long term among economy based on nuclear in these countries.

The short-run Panel NARDL findings indicate that most explanatory variables do not have a statistically significant direct impact on carbon emissions, meaning that short-term changes in economic growth, industrial production, or consumption of nuclear power will not immediately affect the quality of the environment. This implies that the responsiveness of emissions in nuclear economies is not a short-run policy shifts or economic shocks but the long-run structural and technological shifts, which takes time to materialise. The error correction term (COINTEQ) is negative and significant at short run only, which proves the presence of the strong long-run equilibrium association and demonstrates that disequilibrium of approximately 8 percent is corrected only one year after another. This confirms the perception that long-term policy frameworks and technological paths are the key factors determining carbon emissions levels in these economies as opposed to momentary macroeconomic shocks, which serves the ideal suitability of the NARDL model to explain gradual adjustments behaviour.

Table 7
Panel NARDL Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Long-run (Pooled) Results				
GDPG_POS	0.271	0.088	3.064	0.002
GDPG_NEG	0.253	0.099	2.562	0.012
IVA_POS	-0.084	0.035	-2.418	0.017
IVA_NEG	-0.094	0.040	-2.349	0.020
NE_POS	-0.287	0.121	-2.377	0.019
NE_NEG	0.686	0.373	1.837	0.069
@TREND	0.106	0.047	2.219	0.028
Short-run (Mean-Group) Results				
COINTEQ	-0.080	0.011	-7.066	0.000
D(GDPG_NEG)	0.004	0.009	0.433	0.665
D(IVA_POS)	-0.001	0.005	-0.241	0.809
D(NE_POS)	0.138	0.164	0.837	0.404
D(NE_NEG)	-0.306	0.163	-1.874	0.063
C	0.259	0.237	1.093	0.276

The panel-ARDL model robustness in Table 8 supports the long-run validity of the asymmetric outcomes of the panel NARDL model which also strengthens the structural association between the macroeconomic variables and environmental quality in South Asian nuclear-powered economies. The long-run coefficients indicate that the effect of economic growth (GDPG) on carbon emissions is significant and shows that the increased economic activity remains related to the increased environmental pressure which aligns with the state of environmental degradation in the EKC hypothesis. Industrial value added (IVA), however, has a negative and significant long-run coefficient, which is in favor of the assertion that technological upgrading and industrial modernization lead to emissions reduction, which is compatible with a recent study by Mamghaderi et al. (2023); Yang, Shafiq, Nazir, et al. (2024) that point to cleaner production as a process to decouple carbon intensity to industrial activity. In the linear ARDL specification, the long-run coefficient of nuclear energy is statistically insignificant, but this finding explains the usefulness of adopting a nonlinear NARDL specification that better reflects the asymmetrical influence of nuclear energy, as demonstrated in Table 6. The negative and statistically significant coefficient of the error correction term confirms the convergence to the long run, which implies that any deviations in the equilibrium are eliminated with time, although at a moderate pace. Short-run shifts in nuclear power use demonstrate a strong negative impact on the CO2 emissions, which supports the arguments of environmental friendliness of nuclear power use. Overall, the ARDL estimates confirm the strength of the fundamental results and prove that the long-run dynamics prevails over short-term oscillations, which justify the use of nonlinear modelling to reflect the high-level energy-environment interactions.

The findings of the bounds test included in the table 9 validate that there does exist a long run cointegration relation between carbon emissions, economic growth, industrial value added, and consumed nuclear energy across the nuclear economies of India, Iran, and Pakistan. The calculated F-statistics of the multiple cross-sections are higher than the lower boundary and in certain instances, close to or higher than the upper-end, at 5 percent level, which demonstrates that the null hypothesis of non-cointegration can be rejected. This gives powerful empirical evidence that there is indeed a long-term stable linkage between the environmental quality and the macroeconomic fundamentals, justifying the application of the Panel NARDL model which is specifically formulated to capture the long-run equilibrium with asymmetric adjustments. The findings coincide with the recent findings published by Khaliq et al. (2023); Syed et al. (2021), or others, which focus on the idea that structural interdependence becomes evident in the cointegration of an energy-environment model due to long-term policy interventions, technological changes, and energy diversification plans. The cointegration evidence also suggests that short-term non-equilibrium in bulky environmental rates are only temporary and would align at the long-run through endogenous mechanisms, which supports the theory premise that nuclear energy and industrial productivity have long-run contribution to decarbonization pathways.

Table 8
Panel ARDL Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Long Run				
GDPG	0.598	0.190	3.150	0.002
IVA	-0.223	0.079	-2.804	0.006
NE	-0.002	0.225	-0.012	0.990
Short Run				
COINTEQ	-0.085	0.049	-1.740	0.085
D(GDPG)	-0.026	0.021	-1.271	0.207
D(GDPG(-1))	-0.017	0.016	-1.083	0.281
D(GDPG(-2))	-0.010	0.009	-1.056	0.293
D(IVA)	0.010	0.006	1.541	0.126
D(IVA(-1))	0.006	0.005	1.098	0.275
D(NE)	-0.058	0.023	-2.524	0.013
D(NE(-1))	-0.077	0.077	-1.006	0.316
C	0.168	0.203	0.829	0.409
@TREND	0.011	0.009	1.230	0.221

Table 9
Bound Test

Cross-Section	Obs.	F-Stat.				
1	33	5.578				
2	33	2.619				
3	33	4.362				
Critical Values	**10%**		**5%**		**1%**	
Sample Size	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
30	2.907	4.010	3.504	4.743	4.85	6.473
35	2.831	3.879	3.353	4.5	4.849	6.511
Asymptotic	2.49	3.380	2.81	3.76	3.5	4.630

In Figure 1, CUSUM and CUSUM of Squares (CUSUMSQ) plots are shown and are used to assess the stability of the estimated coefficients over time, in the panel NARDL model. Both stability diagnostics show that the cumulative sums do not exceed the critical bounds of 5%, which implies that structural breaks do not exist and that model parameters do not change over the sample period. This implies that the estimated long-run and short-run relations of carbon emissions, consumption of nuclear energy, economic growth and industrial activity are not affected by time-varying disturbances, or changes in regimes. The consistency of parameters confirms consistency of the NARDL model and promotes validity of the conclusions made based on the asymmetric analysis that are in accordance to the econometric guidelines of (Narayan, 2005; Shin et al., 2014), who state that consistent coefficients are a prelude to believable policy implications within the energy-environment model. The stability of CUSUM ensures that the estimated nuclear energy and industrial performance of the environment are structurally compatible and can be reliably utilized to formulate long term policies in nuclear economies.

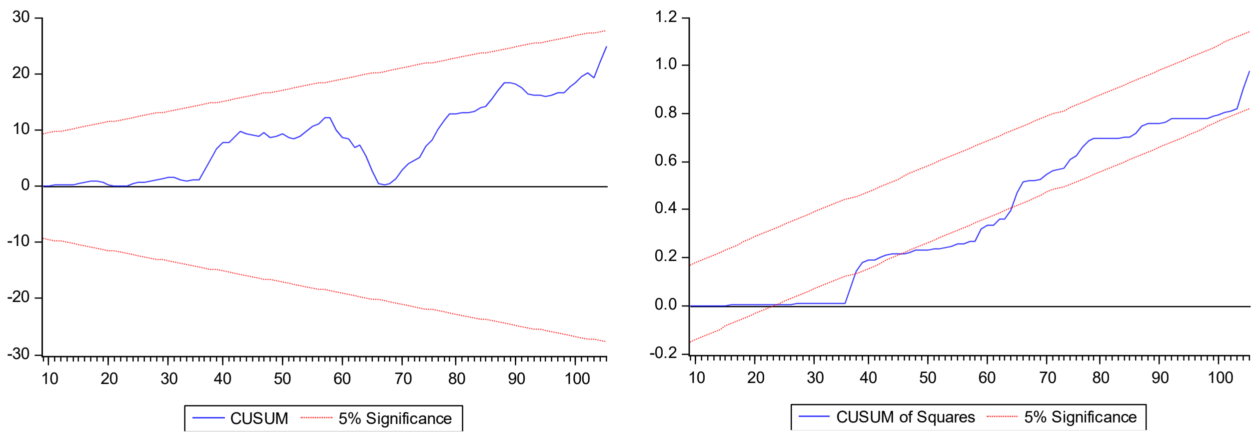

Figure 1: CUSUM and CUSUM Graphs

4.1. NARDL Results Discussion

The results of the cross-sectional NARDL are explained in Table 10 and the results confirmed the negative and significant error correction term which shows that there is correction of deviations of equilibrium over time which validates a stable process of long-run environmental adjustment of India. The positive shocks in industrial productivity (IVAPOS) represent a marginal negative effect of CO2 emissions, which testifies to the slow modernization of India or the revival of cleaner production processes, according to Chen and Santos-Paulino (2013); Destek (2016). Conversely, however, a decline in nuclear energy (NENEG) leads to an enormous rise in emissions, showing that alterations in nuclear power base instigate the shift towards fossil energy, which confirms the asymmetry of the environmental contribution of nuclear energy. These findings are consistent with those of Baek (2016); Khan et al. (2019), who explain nuclear reliability to be an essential factor of emissions minimization. The fact that GDP growth has no major short-run impacts implies that the emissions in India are influenced more by structural changes in energy production rather than one caused by short-term changes in the economy.

The significant and high value of the error correction in Iran confirms the fact that the nation is rapidly adjusting to the long run equilibrium, and nuclear energy is part of its environmental strategy. Nuclear energy consumption (NEPOS) presents positive shocks that would significantly reduce CO2 emissions, which is not surprising as Iran has a more developed nuclear infrastructure, and it uses nuclear energy strategically to decarbonize its energy mix, which aligns with the findings by Jin and Kim (2018); Salim et al. (2014). In contrast, negative shocks (NENEG) enhance the emissions at a significant pace, supporting the sensitivity of the environmental performance in Iran to the fluctuations in nuclear supply. Likewise, negative fluctuations of GDP (GDPGNEG) contribute relevant amounts to emissions, indicating that recessions provide inefficient substitution of energy, a tendency compatible with the hypothesis of pollution based on everyone. Industrial value-added positive shocks make a difference by decreasing emissions, highlighting decarbonization of Iranian advanced technological industrial processes.

The significant and negative error correction term of Pakistan means that the country converges to the equilibrium fast to ensure a stable relationship between macroeconomic variables, energy, and emissions in the long run. Positive industrial activity (IVAPOS) supports the decrease in emissions, which means that the industrial sector in Pakistan should gradually embrace energy-efficient technologies, a fact that resonates with the modernization effect as outlined by Sun et al. (2017). The negative nuclear energy shock (NENEG) causes a substantial increase in emissions, as it is known that Pakistan is increasingly dependable on nuclear energy as an alternative to fossil fuels, like regional results reported by Hassan et al. (2020). In the short term, negative GDP shock (GDPGNEG) has a small impact of decreasing emissions, probably because of reduced production in industries and consumption of less energy during the recession. All these results support the overall point that although Pakistan is moving towards cleaner growth, to reach permanent decarbonization, continuous nuclear power development is necessary.

Figure 2 presents the PMG (Pooled Mean Group) cointegration trajectories for India, Iran, and Pakistan, illustrating the long-run convergence of carbon emissions, economic growth, industrial productivity, and nuclear energy consumption toward a stable equilibrium path. Despite short-term volatility and structural shocks, the plotted residuals consistently revert to equilibrium, confirming the existence of cointegration among the variables, which is consistent with the significant error correction terms established in the panel NARDL estimates. This visual evidence strengthens the econometric justification for using the PMG-ARDL framework**,** as PMG simultaneously accounts for long-run homogeneity across countries and short-run heterogeneity (Pesaran et al., 2001), making it superior to fixed-effect and mean-group estimators. The convergence patterns visible in the graphs further imply that South Asian economies are interconnected in their energy-environment dynamics and tend to adjust back toward equilibrium in response to policy changes or shocks in nuclear energy or industrial growth. This stability validates the theoretical expectation that cleaner energy transition and industrial modernization generate persistent long-term effects on environmental outcomes.

Table 10
Cross sectional NARDL Results

Variable	India	Iran	Pakistan
COINTEQ	0.083	-0.098	-0.059
SE	0.012	0.028	0.012
Prob.	0.000	0.002	0.000
D(GDPG_NEG)	-0.004	0.024	-0.006
SE	0.003	0.008	0.004
Prob.	0.2445	0.010	0.113
D(IVA_POS)	0.003	-0.012	0.004
SE	0.002	0.004	0.001
Prob.	0.114	0.010	0.009
D(NE_POS)	-0.049	0.466	-0.003
SE	0.050	0.200	0.012
Prob.	0.336	0.027	0.779
D(NE_NEG)	-0.179	-0.631	-0.109
SE	0.077	0.183	0.031
Prob.	0.029	0.001	0.001
C	0.014	0.733	0.03
SE	0.013	0.163	0.010
Prob.	0.311	0.000	0.006

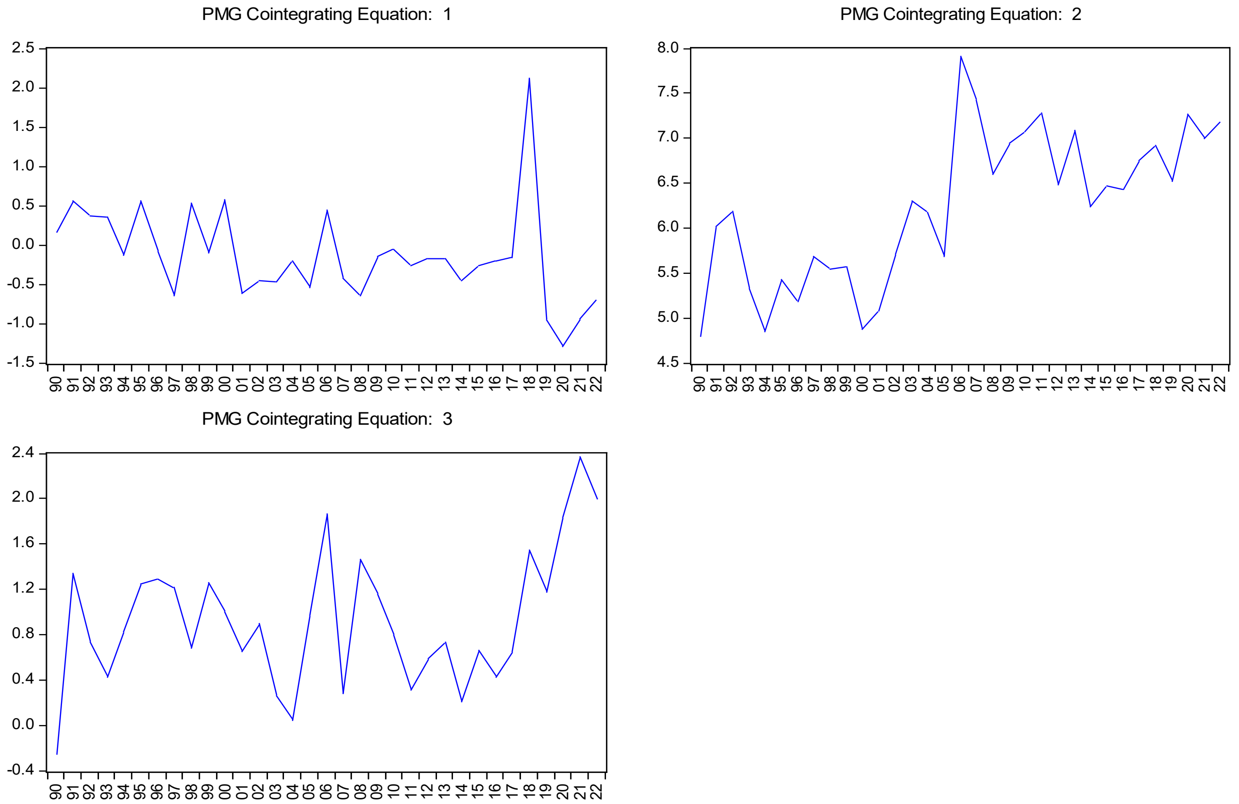

Figure 2: PMG Cointegration Graphs

Table 11 provides the confidence intervals that the estimated asymmetric coefficients in the long run are under the estimation system of the Panel NARDL framework, indicating the advantages of statistical strength and reliability of the model results. The 90% and 95% confidence intervals of both positive and negative shocks to GDP growth (GDPGPOS and GDPGNEG) are all in the positive region, and this confirms that the environmental growth (whether negative or positive) is always associated with environmental degradation in the long run, which again supports our Environmental Kuznets Curve hypothesis during its initial stages. This finding is consistent with recent empirical findings (Ali et al., 2024a; Khezri et al., 2024), as the absence of specific energy policy changes and technological modernization will limit the carbon-intensive economic growth of developing economies. Likewise, the confidence limits of positive and negative industrial value-added shocks (IVAPOS and IVANEG) are below zero at confidence level of 90, 95, which is a strong statistical result indicating that industrial growth with technology progress and modernization would have a mitigating impact on emissions. The result supports the technology section of the IPAT framework, recent discoveries about the role of industrial sophistication and green innovation in helping achieve long-term environmental efficiency (Mamghaderi et al., 2023; Sun et al., 2017; Yang et al., 2025).

Table 11
Coefficient Confidence Intervals

		90% CI		95% CI		99% CI	
Variable	**Coefficient**	**Low**	**High**	**Low**	**High**	**Low**	**High**
GDPG_POS	0.271	0.124	0.418	0.095	0.447	0.038	0.504
GDPG_NEG	0.253	0.089	0.418	0.057	0.450	-0.006	0.514
IVA_G_POS	-0.084	-0.143	-0.026	-0.154	-0.015	-0.177	0.007
IVA_G_NEG	-0.094	-0.160	-0.027	-0.173	-0.014	-0.199	0.011
NE_POS	-0.287	-0.488	-0.086	-0.528	-0.047	-0.605	0.030
NE_NEG	0.686	0.0658	1.307	-0.055	1.428	-0.295	1.669
@TREND	0.106	0.0266	0.185	0.0111	0.201	-0.019	0.231

In the case of nuclear energy (NEPOS), even the confidence intervals are negative and significant at all confidence levels except the most conservative confidence level of 99%. On the other hand, in contrast to negative shocks to nuclear energy (NENEG), where the confidence intervals widen as the confidence level increases, as it can be seen that, even though the 99 percent interval contains zero, the 90 percent and 95 percent intervals still provide a positive and significant magnitude of impact on emissions, demonstrating that nuclear supply disruptions shackle decarbonization progress (Baek, 2016; Mamkhezri & Khezri, 2023). The aggregate validity of these findings is that the estimated asymmetric effects are indeed valid, and to conclude that the long-run associations captured by the Panel NARDL model represent real economic processes and not statistical treatment phenomena, these findings offer persuading empirical evidence of the existence of certain policy interventions, such as clean energy diversification, nuclear investment stability, and industrial technological upgrading.

5. Conclusion

This paper presents a fresh empirical justification of the asymmetric influence of nuclear energy usage, economic development and industrial value added in three nuclear-operative economies of South Asia through a panel NARDL model. The findings validate the hypothesis that economic growth is still positively pushing on carbon emissions, whereas industrial value added can affect emission reduction by technological advancements and improvement of energy productivity. Notably, consumption of nuclear energy exhibits a strong decarbonizing impact over the long run, which justifies its importance as an essential clean energy source in the region. The results provide insights into how unbalanced the energy-environment nexus is to the extent that any reduction of nuclear energy capacity can negate environmental benefits, whereas a continuous increase in capacity leads to emission alleviation in the long run. These findings highlight that South Asia should engage nuclear energy as part of its energy transition processes to achieve anything significant as far as attaining climate sustainability targets are concerned.

This research has some important policy implications, especially for economies that want to strike the right balance between growth and environmental commitments. The findings suggest that policymakers should come up with long-term national energy plans in which the expansion of nuclear energy should be the main low-carbon source of energy policy instead of depending more on fossil fuels. The importance of nuclear infrastructure, safety measures, and the progress of the popularization of nuclear energy is essential to stable energy sources and environmental regulation. Furthermore, the negative correlation between the value added from industrial and carbon emissions indicates that cleaner production methods, green technologies, and policies on industrial innovation should be actively encouraged to decarbonize faster. Sustainability can be achieved attentively to economic development strategies by promoting economic development through specific incentives, regulatory policies, and global collaboration on technology. Moreover, South Asian nuclear safety standards, waste management, and technology transfer may be of significant use in terms of shared costs and general clean energy transition of South Asian countries.

Although it has a high level of methodological rigor and new findings, this study does not lack limitations. The analysis is largely based on country level aggregated data which can mask the sectoral heterogeneity as well as the difference in quality of nuclear infrastructure across nations. Also, geopolitical risks, popular perceptions and institutional limitations that affect the adoption and performance of nuclear energy are not clearly considered in the study. Furthermore, nuclear energy was viewed in the context of being independent of its interplay with the renewable energy sources, which can bring about varying consequences to the environment. Such constraints imply that the study findings are sound in the selected econometric framework, but not that it might exhaust the socio-political scope of nuclear energy use in South Asia.

Since these contributions are made possible in future studies, it is possible to expand on them by adding some interaction terms between renewable technologies and nuclear energy to investigate whether hybrid systems can be able to deliver better decarbonization results. Regulatory quality, geopolitical stability, nuclear safety indicators, and public acceptance measures need to be included in future research to determine the viability and sustainability of nuclear expansion. Moreover, on the sectoral level data might allow more detailed information on the impact of nuclear energy on emissions in industrial, residential, and transportation sectors. It would also be interesting to expand the model to incorporate the carbon pricing mechanisms, financial development, technological innovation, and green foreign direct investment to further inform the nuclear energy-environment nexus. In conclusion it can be said that there is plenty that can be done to enrich the analysis, by applying interdisciplinary methods that combine economic, environmental science, technology policy, and energy governance.

Authors Contribution

Muhammad Azhar Bhatti: conceptualization, data curation, formal analysis, data interpretation, and writing—original draft

Muhammad Nouman Shafiq: conceptualization, critical revision, and writing—review & editing

Conflict of Interests/Disclosures

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